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Microwave irradiation: A sustainable way for sludge treatment and resource recovery

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ABSTRACT

In recent years, microwave (MW) irradiation has gained widespread popularity as an effective thermal method for sludge treatment, mainly due to its rapid and selective heating, energy efficiency, capacity to enhance the yield and quality of product and diminished hazardous product formation and emissions (thus rendering the technique environmentally friendly). The present review aspires to advance understanding of the versatile uses of the MW irradiation technique in sludge treatment, including sludge pretreatment and enhancement in the anaerobic biodegradability of waste sludge and sludge sanitisation, resources (bio-gas, bio-oil, nutrients and heavy metals) recovery and, heavy metals stabilisation. It also summarises future research directions for the better use of MW energy in sludge treatment, process optimisation and developments for industrial-scale implementation of the MW technique and, safety and health related issues.

Contents

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1. Introduction

Management of excess sludge is a serious concern because of continuous increases in sludge production and stringent environmental quality standards [1]. Conventional sludge disposal methods such as incineration, disposal in landfills and in oceans are facing increasing pressure and protest from environmental authorities and from the public domain. Land application of waste sludge as a fertiliser may be an option. However, the presence of pathogens, heavy metals, polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyl (PCB) and dioxins in sludge limits its reuse as fertiliser.

Because of the above-mentioned limitations and limited availability of sludge disposal routes, currently, there is a worldwide interest in three main sludge reduction strategies: (a) sludge reduction in wastewater lines (energy uncouplers and alternating stream exposure to oxic and anoxic environments), (b) sludge reduction in sludge lines (physical, chemical and thermal pretreatments to enhance sludge hydrolysis before anaerobic digestion) and (c) sludge reduction in the final waste lines (incineration and pyrolysis). It is widely documented that pretreatment processes in the sludge line could disrupt the extracellular polymeric substances (EPS) and the divalent cation network and therefore, increase the biodegradability of waste activated sludge (WAS) [2]. The major merits of pretreatment methods (thermal, ultrasonication, acid–alkali, mechanical disintegration and ozonation) are that sludge does not require a dewatering step before the actual treatment and that sludge treatment through hydrolysis is a “clean” technology (e.g., without the need for complex gas cleaning plants such as those used in incineration processes) [3].

Emerging research has focused on the use of MW irradiation technique for thermal treatment of waste sludge. The potential applications of MW energy as remedial alternatives for various types of wastes (contaminated soils, sludge, or wastewater) have attracted steadily growing research efforts during the last decade [4]. This statement is evident from Fig. 1, which shows emerging interest in the use of MW irradiation for sludge treatment via sludge disintegration [5] to enhance anaerobic digestion [6], to stabilise heavy metals [7], to sanitise sludge [8] and to recover resources such as energy-rich biogas [9,10], bio-oil [11] and nutrients [12]. The major driving forces that have engendered this rise in the use of MW technology are that application of MW energy is superior to conventional heating because of its ability to heat rapidly, accelerate reaction rates, provide instant on/off control and increase energy efficiency, which result from its ability to selectively activate or suppress reaction pathways or selectively heat substances. In addition to the thermal effect, the non-thermal effect caused by MW irradiation, and its influence on specific remediation cases, is also an attractive feature of this technology for waste treatment. Thus, MW technology has significant potential as an alternative heating source for the treatment of waste streams and environmental remediation [13].

The present paper is focused on the versatile applications of MW technique in the field of sludge treatment and provide a state of the art review on the (1) fundamental knowledge of MW irradiation, (2) applications of MW irradiation in sludge treatment (sludge solubilisation; improvement in anaerobic digestion; sludge sanitisation; recovery of nutrients, biofuels and heavy metals and heavy metals stabilisation), (3) factors affecting the MW processing of sludge (e.g., MW energy, reaction times, temperatures and sludge characteristics), (4) Associated merits and demerits of MW technique. Furthermore, this review also highlights future research directions and challenges in scaling-up of the MW technique for sludge treatment.

2. Principles of MW irradiation

In the electromagnetic spectrum (Fig. 2) [14], MW irradiation occurs in wavelengths of 1 m^{-1} mm at corresponding frequencies of 300 MHz (3×10^8 cycles/s) to 300 GHz (3×10^{11} cycles/s), respectively [15]. Domestic and industrial MW ovens generally operate at a frequency of 2.45 GHz [16], because they are designed to process foods; and the water in foods is a good absorber of MW irradiation at this frequency. The absorbed MW energy is converted into heat within the material, resulting in an increase in temperature. A uniform MW field generates energy through the realignment of dipoles with oscillating electric fields to generate heat both internally and at the surface of the treated material (Fig. 3). Once a material is exposed to penetrating MW irradiation, some energy is irreversibly absorbed; this, in turn, generates the heat within the volume (or bulk) of the material.

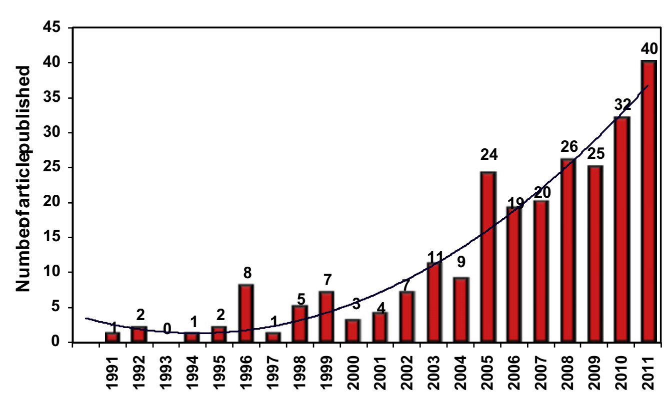

Fig. 1. Annually published research articles on the application of MW irradiation in sludge treatment (http://www.engineeringvillage2.com).

This bulk heating increases the temperature of the materials such that the interior portion becomes hotter than the surface (because the surface loses heat to the cooler surroundings). This is the reverse of the process of conventional heating, in which heat from an external source is supplied to the exterior surface and diffuses toward the cooler interior regions (Fig. 3). Thus, the reverse thermal gradients in MW heating provide unique benefits that include rapid volumetric heating without overheating the surface (non-contact heating, especially in materials with low thermal conductivity) and reduced surface degradation during the drying of wet materials [17,18].

The mechanism of MW irradiation includes a thermal effect and an athermal effect. For MW, the term "athermal effect" generally refers to an effect that is not associated with an increase in temperature [19], while "thermal effect" refers to the process that generates heat as a result of the absorption of MW energy by water or by organic complexes that are marked by either constant or induced polarisation [20]. The athermal effect of MW irradiation is caused by the polarised parts of macromolecules aligning with the poles of the electromagnetic field, resulting in the possible breaking of hydrogen bonds [21]. Sato [22] also proposed that MW energy either caused ions to accelerate and collide with other molecules or caused dipoles to rotate and line up rapidly with alternating (2450 million times/s) electric fields, resulting in changes in the secondary and tertiary structures of the proteins of microorganisms.

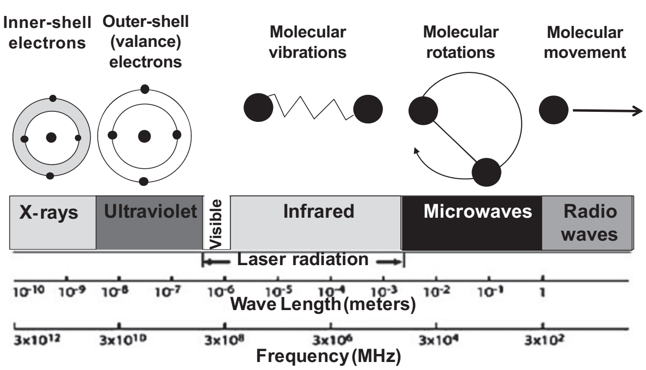

Fig. 2. Electromagnetic spectrum [14].

3. Application domains of MW in sludge treatment

3.1. Sludge solubilisation

MW irradiation is capable of disrupting sludge flocs and cells and releasing organic matter into the soluble phase. The primary organic components found in sludge are carbohydrates, proteins and lipids. Under MW irradiation, the hydrolysis pathway of the organic materials is assumed to be as follows: Lipids are hydrolyzed to palmitic acid, stearic acid, and oleic acid; proteins are hydrolyzed into a series of saturated and unsaturated acids, ammonia, and carbon dioxide; and carbohydrates are hydrolyzed into lower molecular weight polysaccharides and possibly even into simple sugars [23,24]. Yu et al. [5] reported that protein and polysaccharide concentrations increased by 297% and 654%, respectively, upon treatment of sludge at 900 W for 140 s. Eskicioglu et al. [6] found that MW pretreatment at 96 °C caused a 71% increase in soluble protein concentrations. However, the release of soluble organic fraction into the supernatant phase depends on the degree of disintegration at different MW temperatures [25]. Ahn et al. [26] also observed a notable increase in soluble protein, carbohydrate and lipid concentrations with the application of MW. They applied the MW irradiation for 15 min (700 W, boiling point) to disintegrate the WAS (26 g/L total solids, TS) and observed the significant concentration increases from 0.07 to 0.85 g/L for lipids, 0.15 to 0.9 g/L for proteins and 0.07 to 0.9 g/L for carbohydrates.

The increase in the soluble chemical oxygen demand (SCOD) concentration also indicates a significant disruption of complex WAS floc structures and the release of extracellular and intracellular biopolymers (proteins and sugars) from activated sludge flocs to the soluble phase [6] (Fig. 4). Park et al. [27] observed 19% and 22% increases in SCOD concentration after MW pretreatment of WAS (TS-3%) at 91.2 °C and boiling temperature, respectively. Hong et al. [28] applied a treatment temperature of 72.5 °C and observed a notable increase from 8% (control) to 18% in COD solubilisation for MW pretreated WAS (TS-4.1%). Eskicioglu et al. [29] observed that COD solubilisation increased from 9% (control) to 24% after MW pretreatment of sludge (TS-5.4%) at 96 °C. However, in their subsequent study, Eskicioglu et al. [30] applied a higher MW temperature (175 °C) to WAS (TS-3%) and observed

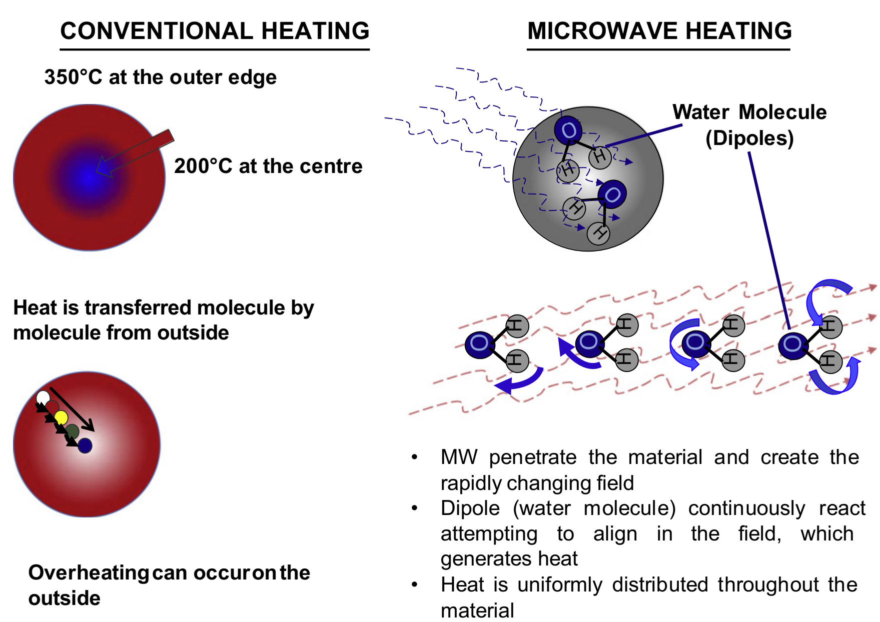

Fig. 3. Difference between conventional heating and MW heating (*Source*: http://ewi.ca/technology/microwave-information.htm).

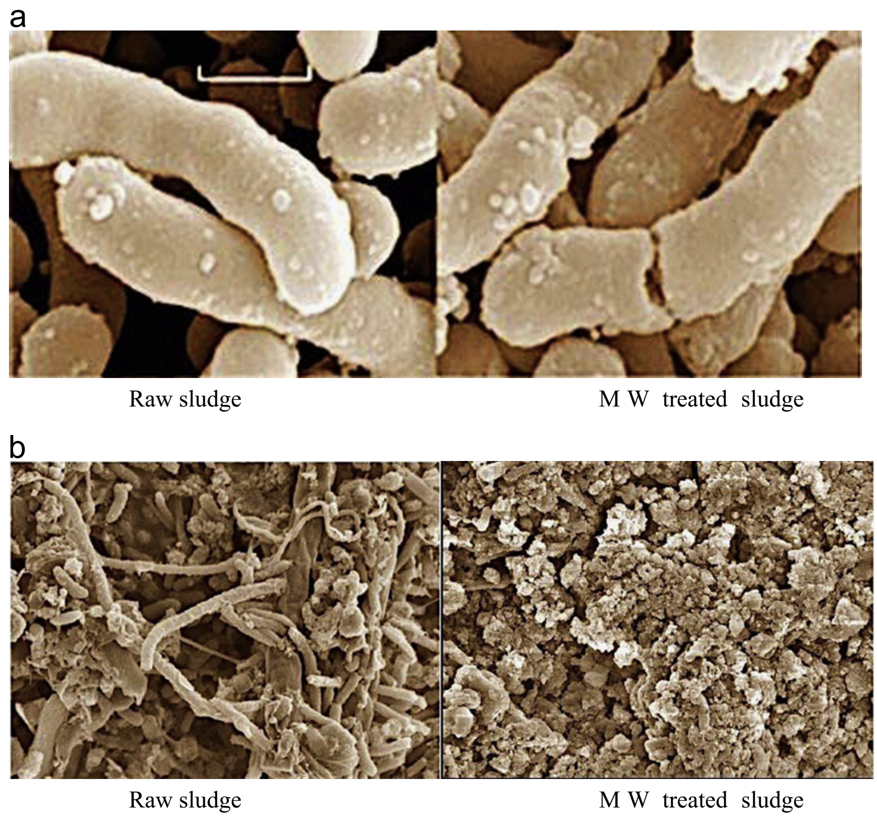

Fig. 4. Scanning electronic microscopic photographs of bacterial cell (a) and sludge samples (b) before and after MW treatment shows the ruptured and broken microbial cells [a-26, b-110].

a significant increase from 9% (control) to 35% in COD solubilisation. Toreci et al. [31] also applied a similar MW temperature (175 °C with 3.75 °C/min MW intensity) for the pretreatment of sludges with two different concentrations of solids (6% and 11.85%). They observed that COD solubilisation improved from 10% (control) to 46% and 7% (control) to 57%, respectively. Eskicioglu et al. [2] reported that COD solubilisation increased from 9% (control) to 24%, 24%, 28% and 35% at pretreatment temperatures of 96, 120, 150 and 175 °C, respectively. Similarly, the VS/TS ratios of WAS increased from 8% (control) to 19%, 21% and 32% after MW irradiation of WAS (TS-4.6%) at 120, 150 and 175 °C, respectively. Thus, the increases in the rates of COD solubilisation were found to be proportional to the increases in MW treatment temperature. Beszédes et al. [32], applied MW heating (5 W/g and 30 min) to treat the dairy sludge, and they observed a significant enhancement in COD solubilisation (up to 57%) and in the VS/TS ratio (up to 32%).

Tang et al. [33] investigated the energy consumption during the MW pretreatment of excess sewage sludge. They observed that high water content is unfavorable for the solubilisation of solids at a given energy input, whereas at lower water contents, less energy input would lead to a larger sludge solubilisation. More energy was consumed in increasing the temperature of the sludge with a higher water content, which decreased the energy efficiency in sludge solubilisation. Gabriel Coelho et al. [34] studied the effects of MW heating (1250 W, 96 °C, 6 min) for the pretreatment of thickened WAS at 100% MW intensity. They observed a remarkable increase in COD solubilisation from 6% (control) to 20%, which indicates the potentially easier or faster digestion of organic matter present in the sludge.

Therefore, an extensive review of the literature shows that the COD solubilisation was improved up to 20% and 26% after pretreatment of WAS at boiling (96 °C) and higher treatment temperatures (up to 175 °C), respectively (Table 1). Thus, the MW irradiation method was shown to be successful for effectively disintegrating sludge flocs and thus increasing the biodegradable portion from solids content to in the bulk liquid phase of sludge. However, the degree of sludge solubilisation will be affected by several factors like, water content, solids concentration, sludge type (primary, secondary, mixed), treatment temperature, power intensity and reaction time.

3.2. *Enhancement of anaerobic digestion*

Anaerobic digestion is used as an economical and convenient method to treat both municipal and industrial sludge. However, its application has often been limited because of long retention times (20–50 days) and low degradation efficiency (20–50%); these problems are generally associated with the slow hydrolysis (one of the three stages of the anaerobic digestion process that includes hydrolysis, acetogenesis and methanogenesis) of WAS [37]. Several researchers have shown that MW irradiation is an efficient pre-hydrolysis step to efficiently disintegrate biosolids and to enhance the subsequent anaerobic digestion of MW-pretreated sludge. Park et al. [27] reported higher VS reduction (25.7%) in the anaerobic reactors treating MW-pretreated sludge as compared to the control reactors (23.2%). Furthermore, 64% and 79% improvements were observed in total COD removal and in methane production, respectively, from the subsequent mesophilic digestion of MW-pretreated sludge. Thus, anaerobic digestion of MW-pretreated sludge reduced the reactor SRT from 15 to 8 days. Hong et al. [28] observed 68% more biogas production at 5 days SRT for the reactor digesting MW-pretreated sludge (72.5 °C) in comparison of the control reactors operating at 11 days SRT. Pino-Jelcic et al. [38] observed a 53.9% VS reduction for MW pretreated-anaerobically digested sludge, which was higher

Table 1
Effect of different MW pretreatment on sludge solubilisation.

Treatment temperature (°C)/time (min)	TS concentration (%)	COD solubilization (%)		% Enhancement	Reference
		From (raw)	To (treated)		
Low temperature					
72.5 °C	4.1	8	18	10	[28]
Near/at boiling point					
91.2 °C, 7 min	3.0	2	19	17	[27]
Boiling, 15 min	3	2	22	20	[27]
96 °C, 5 min	5.4	9	24	15	[29]
Boiling, 15 min,	2.5	2	22	20	[26]
96 °C, 6 min	–	6	20	14	[34]
Medium temperature					
120 °C, 10 min	–	3	15	12	[35]
120 °C (400 W), 14.3 min	2	6.5	17.5	11	[36]
High temperature					
175 °C	3	9	35	26	[30]
175 °C	4.6	9	35	26	[2]

than the conventionally heated–digested sludge (51.3%) or the control (49.0%). MW-digested sludge showed higher biogas production by 16.4 and 6.3%, as compared to control and conventionally heated–digested sludge, respectively. Eskicioglu et al. [29] suggested that the anaerobic digestion of WAS (TS-5.4%) that was microwaved at 96 °C (50% MW intensity) enhanced its ultimate degradability and produced the highest amount of biogas with 21% increases over the controls after 19 days of digestion. Furthermore, Eskicioglu et al. [25] observed that MW-acclimated inoculum (treated at 96 °C) produced 16% more biogas compared to the control after 15 days of mesophilic batch digestion of pretreated WAS. Kennedy et al. [39] also observed a 12% and 16% improvement in VS destruction and in methane production, respectively, during anaerobic digestion of MW-pretreated sludge (85 °C). Park and Ahn [40] investigated the effectiveness of MW pretreatment (80 °C) over the conventional thermal pretreatment (80 °C). They reported the significant improvement of 89.3 and 60.6% in COD removal efficiency and biogas yield, respectively, for MW in comparison of conventional thermal pretreatment at an HRT of 5 days

On the other hand, anaerobic digestion of the microwaved sludge (pretreated at higher temperature) was reported to achieve higher digestion efficiency and greater biogas production over the sludge microwaved at lower temperatures (<100 °C). In two subsequent studies, Eskicioglu et al. [2,30] observed 31% higher biogas generation than the control reactor during mesophilic digestion of MW-pretreated (175 °C) sludge (3% TS). Toreci et al. [41] applied the MW temperature of 175 °C with 3.75 °C/min MW intensity to treat the sludge and observed a significant improvement in biogas production (from 676 to 839.6 L biogas/kg VS) with a moderate decrease in VS removal (from 49.9 to 43.4%) at 10 days SRT in comparison of the control run at 20 days SRT. However, 83% greater biogas production was observed for MW-pretreated sludge at 5 days SRT if compared with the control digester operated at 20 days SRT. MW pretreatment of WAS at higher specific energy was reported to significantly improve the efficiency of anaerobic digestion; however, the differences in sludge water content have relatively less impact on biogas production [33]. Two-stage thermo–thermo reactors were used to digest the MW-pretreated (1250 W, 96 °C, 6 min) thickened WAS. A maximum VS removal of 53.1% (SRT, 15 days) and a 106% increase in biogas production were observed as compared to the control reactor [34]. MW pretreatment and staging reactors allowed the application of very short SRT (5 days) with no significant decrease in reactor performance (in terms of VS removal) in comparison with the control reactor. Saha et al. [42] also reported the effectiveness of MW pretreatment in pulp mill sludge solubilisation and subsequent anaerobic digestion over the ultrasonic and Microsludge® pretreatment methods.

Therefore, 16–20% higher biogas yields (in comparison with control) and up to 54% VS removal can be achieved during the anaerobic digestion of MW-pretreated sludge (at boiling temperature). However, 31% higher biogas yield (in comparison with control) and 68% VS removal can be achieved after anaerobic digestion of MW pretreated WAS (175 °C) (Table 2). Accordingly, the MW irradiation method effectively disintegrates the sludge flocs and leads to microbial cell lysis that releases biodegradable organic materials and makes them readily accessible to anaerobic digestion. This process ultimately leads to enhanced VS reduction and biogas production during the anaerobic digestion of MW-pretreated sludge and reduces the SRT remarkably.

3.3. *Sludge dewaterability*

Sludge dewatering is an elementary step in sludge processing because it reduces the sludge volume and the cost of sludge transportation for disposal. MW irradiation is considered to be an efficient tool for improving sludge dewaterability because of its "thermal" and "athermal" effects [24,29,45]. Wojciechowska [24] applied MW irradiation (3 min reaction time) for sludge conditioning and observed 73% and 84% decreases in specific resistance to filtration (SRF) of mixed sludge (primary + WAS) and anaerobically digested sludge, respectively. MW-treated sludge showed better dewaterability than conventionally heated and non-pretreated sludge. MW-treated sludge showed significant improvements of 17.6% and 13.8% in dewatering rates in comparison with control and conventionally heated/digested sludge [38]. Eskicioglu et al. [29,30,35,43] carried out several studies to investigate the effects of MW pretreatment on sludge dewaterability. They reported an approximately 40% improvement in dewaterability (by capillary suction time, CST) of anaerobically digested sludge pretreated at 96 °C. A significant reduction from 181 s to 158 s was observed in CST values of anaerobically digested sludge (TS, 5.8%) that was pretreated at 120 °C for 10 min. Furthermore, a 75% improvement was registered in the dewaterability of anaerobically digested sludge (33 °C) that was pretreated at 175 °C. Furthermore, Yu et al. [45] reported that the anaerobic digestion of MW-pretreated sludge remarkably improved the sludge dewaterability, and the CST values decreased from 900 s (control) to approximately 300 s (a 60% reduction in CST values). A MW input of 900 W and a 60 s reaction time was suggested to be an ideal pretreatment for maximum sludge dewaterability. The above-mentioned pretreatment conditions improved the sludge settleability by enhancing the settling

Table 2
Effect of MW pretreatment on the performance of anaerobic digestion.

Treatment conditions	Anaerobic digestion	Findings	Reference
91.2 °C, 7 min	35 °C, SRT 15 days	25.9% VS reduction 23.6% TCOD removal 64% and 79% improvement in TCOD removal and in methane production. Anaerobic digestion of MW pretreated sludge reduced the reactor SRT from 15 days to 8 days	[27]
96 °C, 3% TS	Batch, 33 ± 1 °C 5 day SRT	30% Higher biogas production over control reactor and 26% higher VS removal	[43]
85 °C	Batch 35 °C, 25 days SRT	12% and 16% improvement in VS destruction and in methane production, respectively	[39]
175 °C, 3% TS	mesophilic batch, 35 ± 1 °C	31% Higher biogas production than the control	[2,30]
170 °C, 30 min	Batch, 35 °C, 30 d SRT	25.9% Higher biogas production, 12% higher VS removal over control	[44]

Table 3
Effect of MW treatment on the sludge dewaterability.

MW treatment conditions	Findings	Reference
550 W, 3 min	73% and 84% decrease in SRF of mixed sludge (primary + WAS) and anaerobically digested sludge, respectively	[24]
96 °C	40% Improvement in dewaterability (by CST) of anaerobically digested sludge	[29]
120 °C for 10 min	Significant reduction from 181 s to 158 s in CST values of anaerobically digested sludge	[35]
175 °C	75% Improvement in dewaterability of anaerobically digested sludge (33 °C).	[30]
175 °C (3.75 °C/min)	Significant decrease from 900 s (control) to 600 s in CST values for the MW pretreated WAS.	[41]
900 W and 60 s reaction time	CST values decrease from 900 s (control) to approximately 300 s (60% reduction in CST values).	[45]

velocity of sludge (45 mm/h), which was faster than the peak value of the settling velocity for the untreated sludge (39.6 mm/h). Toreci et al. [46] reported that the dewaterability of digested sludge was improved at higher pretreatment temperature (175 °C) and lower microwave intensity (3.75 °C/min). The corresponding percentage decreases in CST was 74% in comparison of the control sludge, respectively.

Therefore, 40% and 60–75% improvements in sludge dewaterability (in terms of CST) were achieved after anaerobic digestion of MW-pretreated sludge at lower (boiling point) and higher (175 °C) treatment temperatures, respectively (Table 3). Thus, the MW-enhanced pretreatment of sludge and subsequent anaerobic digestion showed a significant improvement in sludge dewatering characteristics and sludge settleability over the conventional heating methods. Moreover, the studies reported that greater level of MW energy and shorter contact times are needed to achieve higher sludge dewaterability. The sludge flocs (repositories for water) are broken down into smaller fragments at short contact times, and these smaller fragments can be re-flocculated to coarser particles with flocculation agents; which ultimately can lead to a significant improvement in sludge dewaterability [45].

3.4. Pathogens removal

MW-irradiation technique was reported to be effective in destroying pathogens in sewage sludge and biosolids. In the temperature range between 57 °C and 68 °C, MW irradiation caused a greater decrease in bacterial activity than did external heating. However, bacterial activity was observed to almost cease above 68 °C [19]. The athermal effects of MW are resulting in the possible breaking of hydrogen bonds and leads to denaturation and death of microbial cells [21,47]. Moreover, the cell membrane is a selectively permeable lipid bi-layer, and lipids absorb MWs; thus, it is possible that MW irradiation causes substantial damage to cell membranes, resulting in the release of intracellular materials and finally leading to the cell death. A number of studies have indicated that MW irradiation could affect the delicate chromosomal structure and function and the tolerance of cells to standard mutagens and lesion repairs [15,48,49].

Liao et al. [50] observed that the pretreatment of sludge at 100 °C for 5 min could possibly destroy most of the pathogens; however, no microorganism activity was observed above 100 °C. Martin et al. [51] reported that MW treatment significantly reduced the number of total coliforms bacteria in sewage sludge, and no fecal coliforms activity was observed after pretreatment of sludge at 85 °C. Furthermore, Class-A sludge can be produced constantly with continuously fed mesophilic anaerobic digesters using MW-pretreated (at 65 °C) sludge [28]. Pino-Jelcic et al. [38] observed a 4.2-log reduction in fecal coliforms numbers for MW-pretreated (1000 W, 65 °C) and digested sludge, whereas 2.9- and 1.5-log fecal coliforms reductions were observed for conventionally heated–biodigested sludge and control sludge, respectively. Park et al. [36] showed that coliforms and *Escherichia coli* (*E. coli*) were not detected in sludge that was pretreated at 70 °C for 5 min. The degree of cell membrane damage was observed to increase with energy consumption. Under low doses of MW irradiation ($Es = 30$ J/mL), the cell covering disappeared; the cell membrane was intact, but the intracellular substances were destroyed. Using a relatively higher energy input ($Es = 75$ J/mL), the cell membrane split and some intracellular substances were released. As the energy input continued to increase ($Es = 120$ J/mL), the cell membrane was broken down, all of the intracellular contents were released, and the cell membrane continued to disintegrate into increasingly smaller pieces under the athermal effects of MW irradiation [33]. Gabriel Coelho et al. [34] reported that, even at an SRT of 5 days, the two-stage thermo–thermo reactors treating pretreated, thickened WAS (1250 W, 96 °C, 6 min) produced a sludge with a low total coliforms content (3.7 CFU/g TS) that fulfilled the criteria for Class-A sludge.

The extensive review of the available literature shows that the MW-irradiation technique is capable of significant pathogens destruction at 70–100 °C treatment temperatures and that it can produce environmentally safe sludge (Table 4). MW irradiation immediately attacks cell membranes and thus lowers bacterial activity. After a certain amount of energy accumulation, cell damage and the subsequent bacterial activity reduction occurs rapidly above 57 °C [19]. Therefore, in addition to their use for pasteurisation and sterilisation in the food industry, MW-irradiation techniques could be adopted for sludge pasteurisation. Nevertheless, the effect of

Table 4
Effect of MW treatment on the pathogen inactivation.

MW treatment conditions	Findings	Reference
> 68 °C	Bacterial activity almost ceased	[19]
100 °C for 5 min	Possibly destroys most of the pathogen	[50]
> 100 °C	No microorganisms activity was observed	
85 °C	No fecal coliforms activity was observed	[51]
65 °C	Class A sludge can be produced constantly with continuously fed mesophilic anaerobic digester using MW pretreated sludge	[28]
1000 W, 65 °C	Fecal coliforms reduced by 4.2 log	[38]
70 °C for 5 min	Coliforms and *E.coli* were not detected	[36]
100% MW intensity 1250 W, 96 °C, 6 min	Two-stage thermo–thermo reactors treating MW pretreated thickened WAS produced the sludge with low total coliforms content (3.7 CFU/g TS), and fulfill the criteria of Class A sludge, even at a SRT of 5 days	[34]

Table 5
Effect of hybrid MW–alkali pretreatment on sludge solubilisation.

Treatment conditions	Findings	References
2 g/L alkali (NaOH) dosage 85 °C	COD solubilisation was increased from 2% (control) to 21.7%.	[39]
120–170 °C and 0.2 g NaOH/g dry solids dosage – 5 min reaction time	50–70% VSS solubilisation and 80% COD solubilisation.	[54]
160 °C with NaOH (pH 12)	COD solubilisation increased significantly from 0.5% (control) to 34%, 43.5% improvement was observed in biogas generation in comparison of control.	[55]
210 °C – 0.2 g NaOH/g SS – 35 min reaction time	85.1% of VSS solubilisation 14% higher methane production than the control reactor.	[56]
MW-alkali (600 W – 2 min and 1.5 g/L NaOH dose, pH-12 for 10 min)	Significant increase from 0.33% (control) of 45% in COD solubilisation after pretreatment of WAS.	[57]
MW-alkali (900 W – 95 °C and pH 12)	COD solubilisation enhanced from 0.5% (raw) to 52.5% (MW–NaOH)	[8]

different MW treatment conditions on removal of coliforms microorganisms are studied widely, no information is available on the fate of spore and cyst forming organisms and Enteroviruses under low and high MW thermal treatment conditions. Thus, for safe disposal and land application of biosolids, it is necessary to study the effect of MW treatment on the spore and cyst forming organisms and Enteroviruses.

3.5. Hybrid pretreatment of waste sludge

Hybrid techniques are the coupling of a physical or mechanical method with a chemical method. Currently, these techniques appear to be an attractive alternative due to their higher efficacy over a single technique. With this synergism, the efficiency of a chemical dosage can be improved significantly, and the process leads to the disaggregation of coarse and dense biological flocs induced by the physical or mechanical action [52].

3.5.1. MW—alkaline/acid

Previous studies have reported that the combined thermo-chemical pretreatment achieved significantly higher VSS solubilisation over individual thermal and chemical treatments of sludge [53]. However, the conventional thermal or thermo-chemical treatments are time-consuming. Therefore, combined MW-chemical treatments provide an alternative method for sludge treatment. Table 5 summarises the core findings of the main studies that were conducted to investigate the effects of hybrid MW-alkali pretreatments on sludge solubilisation.

Kennedy et al. [39] reported that COD solubilisation increased from 2% (control) to 21.7% after pretreatment of sludge with a 2-g/L alkali (NaOH) dose at 85 °C; this increase was significantly higher than that of individual MW (7%) and alkaline treatments (16.3%). However, there was not a significant effect of the combined alkali-MW pretreatment on the anaerobic degradability of pretreated sludge or on biogas production. Eskicioglu et al. [30] observed a 54% ultimate sludge solubilisation after MW-alkali treatment of WAS at 175 °C with a 2-mol NaOH/L dose and two-week reaction time. Qiao et al. [54] reported that MW heating alone reduced 40% of VSS at 170 °C, while addition of 0.05-g NaOH dose per g dry solids increased the VSS dissolution ratio to 50% and achieved a 35% SS reduction. Dogan and Sanin [55] observed that COD solubilisation was increased significantly from 0.5% (control) to 34%, however, a 43.5% improvement was observed in biogas generation (in comparison with the control) for WAS that was pretreated at 160 °C with NaOH (pH12). Moreover, TS, VS and TCOD reductions were improved by 24.9%, 35.4% and 30.3%, respectively, at 15 days SRT. Chi et al. [56] reported that 85% VSS solubilisation could be achieved after pretreatment of sludge at 210 °C with a 0.2-g NaOH/gSS dose and 35 min reaction time. All digesters fed with MW-pretreated WAS were observed to achieve 14% higher methane production than the control reactor. Chang et al. [57] observed a significant increase of 45% in COD solubilisation after MW–alkali (85 °C and pH12) pretreatment of WAS. This was notably higher than the individual MW (8.5%) and alkali (18%) pretreatments with similar treatment conditions. Similarly, Tyagi and Lo [8] reported a 20% higher COD solubilisation (52.5%) for combined MW–alkali pretreatment, if compared to the sum of individual MW and alkali pretreatment methods ($16\%_{MW}+28.4\%_{NaOH}=44.4\%$) alone. Jang and Ahn [58] studied the effect of combined MW–alkali pretreatment methods on thickened WAS and subsequent mesophilic anaerobic digestion. They reported that the degree of substrate solubilisation was 18 times higher in pretreated sludge (53.2%) than in raw sludge (3.0%), as well as, biogas production was 20% higher in comparison of control at 5 days.

Thus, the previous findings shows that the combination of MW thermal pretreatment with alkaline method can synergistically enhanced the sludge solubilisation and subsequent anaerobic digestion over the individual MW and alkaline pretreatment methods. The MW pretreatment alone is energy intensive process for achieving high degree of sludge solubilisation; however, the integration of alkalisation with MW method will be advantageous to reduced the MW energy consumption and corresponding treatment cost for achieving the similar solubilisation yield, as by MW alone.

Table 6
Effect of hybrid MW-AOP pretreatment on sludge solubilisation.

Treatment conditions	Findings	Reference
MW (20 °C/min) for 5 min and 71 mL/L H_2O_2 dosage (30% by wt)	Over 96% of TCOD was dissolved into the solution	[59]
80 °C–5 min, 1 mL H_2O_2 (30%)/1%TS dosage, 2.9% TS	25% Increase in SCOD	[60]
MW/H_2O_2 (1%)–AOP, 80 °C–3 min	18% Increase in COD solubilisation	[61]
120 °C–10 min, 1 g H_2O_2 (30%v/v)/g TS-6.4%.	COD solubilisation increased from 3% (control) to 24%	[35]
80 °C-3 min with 2% H_2O_2 dosage TS-0.5%	SCOD reached as high as 87% of total COD	[63]
70 °C–0.1% H_2O_2 dosage	Maximum SCOD concentration was approximately 1000 mg/L (25% of TCOD of the initial sludge)	[20]

3.5.2. MW-enhanced advanced oxidation process (MW/H_2O_2-AOP)

Advanced oxidation process (AOP) is clean and efficient and can be classified as one of the green technologies for the treatment of sludge [134]. AOP relies on the generation of reactive free radicals, especially hydroxyl radicals ($^{\bullet}OH$), which is a highly powerful oxidizing agent with an oxidation potential of 2.33 V. It provides faster reaction rates; however, the operational cost of AOP is relatively high [17].

Table 6 sums up the major findings of the works carried out to investigate the effect of hybrid MW-AOP pretreatment on sludge solubilisation. Liao et al. [59] reported that over 96% of TCOD was dissolved into the solution after MW pretreatment (20 °C/min) for 5 min with a 7-ml/L H_2O_2 dose (30% by wt). Chan et al. [12] observed that all of the COD in the sewage sludge was obtained in soluble form at 80 °C with a 34-mL/L H_2O_2 + 17 mL/L H_2SO_4 dose, indicating that all of the organic material was solubilised. Kenge et al. [60] observed a 25% increase in SCOD upon pretreatment of WAS (2.9% TS) at 80 °C (5 min heating time) with 1-mL H_2O_2 (30%)/1%TS dosage. Lo et al. [61] reported the 18% increase in COD solubilisation after pretreatment of WAS by MW/H_2O_2 (1%)–AOP at 80 °C for 3 min. Eskicioglu et al. [35] reported that COD solubilisation increased from 3% (control) to 24% after a combined MW (120 °C for 10 min) and AOP pretreatment (1 g H_2O_2 (30%v/v)/g TS) of WAS (6.4% TS w/w); this indicates a synergistic disintegration effect upon the combination of both treatments. They concluded that elevated MW temperatures (> 80 °C) increased the decomposition of H_2O_2 into $OH^{\bullet}$ radicals and enhanced both the oxidation and the particulate COD disintegration of WAS samples. However, no significant effect of the combined MW-H_2O_2 treatment was observed on methane production and sludge dewaterability. Wang et al. [62] applied MW (80 °C) heating for the pretreatment of WAS, followed by the addition of H_2O_2 and then continuous heating to 100 °C. They observed that the higher the H_2O_2 dosing ratio, the more the SCOD was released into the supernatant.

Thus, the hybrid pretreatment methods have shown their superiority over the individual pretreatment methods by synergistically enhancing the sludge disintegration. The combined treatment reduces the energy consumption, chemical use and reaction time when compared to individual/combined chemical and conventional heating methods. However, research on the application of MW coupled hybrid pretreatment techniques is presently in its infant stage. Therefore, satisfactory research in this direction can lead policy makers and environmental protection agencies to choose the most robust and sustainable solutions for sludge management.

3.6. Resource recovery

3.6.1. Nutrients

Sewage sludge contains considerable amounts of nutrients, especially phosphorus (0.5–0.7% TS) and nitrogen (2.4–5.0% TS) [64]; these nutrients exist mainly in the form of proteinaceous material. The breakdown and solubilisation of sludge biomass and its subsequent conversion to ammonia and phosphates could potentially be used to produce plant fertilisers such as magnesium ammonium phosphate (struvite), which can be used directly for soil application [84,87,88]. Thus, the challenge is to develop a sustainable nutrient management strategy that can effectively recover these nutrients and produce a useful product [65].

In recent years, much effort has been directed towards phosphorus recovery from sewage sludge via crystallisation, which has been developed and implemented in Japan and The Netherlands [66,67]. Calcium phosphate and magnesium ammonium phosphate (struvite) are end products that are commonly recovered from these processes and can be used as an excellent plant fertiliser because of its slow release properties [68]. In order to recover the phosphorus from sewage sludge via crystallisation, it is necessary to undertake a P-solubilisation process to release phosphate to the supernatant [50]. Many P-solubilisation processes have been developed [69–72]; however, these processes require either the addition of chemicals to initiate reactions or a longer reaction time. Therefore, MW heating was applied by various researchers for rapid and efficient nutrient recovery.

Liao et al. [50] reported that up to 76% of total phosphate (TP) could be released into solution using a MW heating time of 5 min. Bacterial cells and difficult-to-degrade organic compounds could be destroyed during the exposure to MW irradiation, which ultimately causes the release of stored polyphosphate and the phosphorus trapped in extracellular polymeric material into the solution. Ammonia is also released with the phosphate [71]. Liao et al. [74] used an advanced oxidation process (AOP) that combined H_2O_2 and MW heating for the solubilisation of phosphate in WAS that was collected from an enhanced biological phosphorus removal (EBPR) process. The MW irradiation was used in the process as a generator agent of oxidizing radicals and as a heating source. More than 84% of the total phosphorous was released at 170 °C (5 min exposure time) with a 50-mL/L H_2O_2 (30 wt%) dose. Wong et al. [75] observed that the combination of H_2O_2 and acid hydrolysis resulted in up to 61% of total phosphorus and 36% of TKN released into the solution at 100 °C and 120 °C (5 min exposure time), respectively. Chan et al. [12] observed approximately 70% phosphorus solubilisation and 47% ammonia solubilisation (as TKN) after treatment of WAS with a single-stage MW (120 °C)/H_2O_2 (35 mL/L)/H_2SO_4 (17 mL/L) treatment. Wong et al. [76] registered the maximum ammonia solubilisation (217 mg N/L) at 200 °C with a 2-mL H_2O_2 dose, which represented a 52.6% TKN release into the solution. More than 95.5% of the initial TP was released into the bulk solution at 200 °C with 2-mL H_2O_2 and 0.5-mL H_2SO_4 doses. Danesh et al. [73] reported that the soluble fraction of phosphorus was increased from 31% to 38% for un-thickened sludge after increasing the MW heating temperature from 50 to 70 °C; this is significantly greater solubilisation than that observed with conventional heating. In this way, a 23–25% reduction can be achieved in phosphorus loading to the anaerobic digesters. According to

Table 7
Effect of MW treatment in nutrient recovery.

Treatment conditions	Findings	Reference
1000 W, 5 min, 100 °C	Up to 76% total phosphate (TP) could be released into the solution	[50]
170 °C for 5 min with 50 mL/L H_2O_2 (30 wt%) dose	More than 84% of the total phosphorous was released	[74]
5 min at 100 °C+H_2O_2 3 wt% 5 min at 120 °C+H_2O_2 3 wt%	61% of total phosphorus 36% of TKN released	[75]
MW(120 °C)/H_2O_2 (35 ml/L)/H_2SO_4 (17 mL/L)	70% phosphorus solubilisation and 47% ammonia solubilisation (47% as TKN).	[12]
200 °C and 2 mL H_2O_2 dose	52.6% TKN release	[76]
200 °C and, 2 mL H_2O_2 and 0.5 mL H_2SO_4 dosages	95.5% TP release	
120 °C for 5 min and 2 wt% of H_2O_2 dose	76% as orthophosphate/TP and 19% as NH_3/N release	[63]
900 W for 1 min	45% increase in NH_4–N concentration	[5]
70 °C and 0.1 wt% H_2O_2 dosage	10% phosphorus release as ortho-phosphorus	[20]

Table 8
Effect of MW treatment in heavy metals recovery.

Treatment conditions	Findings	References
90 W, 30 s, sewage sludge	Higher recoveries of Ni (98.8%), Zn (100.2%), Cu (93.3%), Pb (442.5%)	[85]
10 min, 800 W using sulfuric acid, industrial sludge.	85% Cu was leached from industrial sludge	[79]
70 °C, 90 min, TWAS	Significant release of As (63%), Mb (61%), Ni (37%), and Cu (27%) into the solution	[73]
900 W and 60 s, sewage sludge	Overall metal recoveries (Cd, Cr, Cu, Ni, Pb, Zn) of 95.3 to 104%	[88]
800 W for 20 min-H_2SO_4 (1 N)	90% of Cu can be extracted from coarse sludge ($<$9.5 mm) and fine sludge ($<$150 μm)	[89]

Table 7, the use of MW irradiation alone could increase the quantities of TP and TKN in soluble phase that are released up to 76% and 36%, respectively, at a moderate temperature (100 °C) and a short (5 min) reaction time. Moreover, combined use of MW and an advanced oxidation process was observed to accelerate the release of TP and TKN up to 95.5% and 53%, respectively, after pretreatment of WAS at a high temperature (200 °C) with low chemical dosages (2-mL H_2O_2 and 0.5-ml H_2SO_4). Thus, MW technology could be a promising method for enhanced nutrient (phosphate and nitrogen) recovery from waste sludge.

3.6.2. *Heavy metals (recovery and stabilisation)*

Heavy metals such as zinc (Zn), copper (Cu), nickel (Ni), cadmium (Cd), lead (Pb), mercury (Hg) and chromium (Cr) are the principal elements restricting the use of sludge for land application due to probable soil and ground water contamination, which ultimately affect the human and animal health. Therefore, appropriate treatment of the waste sludge is necessary before landfill disposal. Commonly, the metal-bearing sludges are treated to extract the metal ions from the wastes sludge, or stabilise the metals in solid forms. The strategies of metal-stabilisation methods include concentrating metals in an area with an electrode, cementing metals with concrete or polymeric materials, or transforming metals into high temperature phases via thermal reactions. All of the methods are capable of effectively reducing the mobility of metal ions [77]. Among the thermal treatments, MW technique has been widely applied for the remediation of waste materials, such as pyrolysis of sewage sludges [78], MW-assisted extraction and digestion [79], and stabilisation of metal ions in soils or sludges [80–82].

3.6.2.1. Heavy metals recovery. Most of the metal ions in sludge can be recovered by extraction using acid treatment. Furthermore, MW energy also has the potential to be used in metal recovery operations, such as heating, drying, leaching, roasting/smelting and waste management [83]. Rapid solvent extraction [84] and the fast wet dissolution of various types of solid samples [85,86] are some of the well-known applications of MW. Table 8 summarises the core findings of the main studies that were carried out to investigate the use of MW in heavy metals recovery. Perez-Cid et al. [85] applied the four-stage Tessier sequential extraction method for metal fractionation in a sewage sludge sample. They observed the similar recoveries of Ni (98.8%), Zn (100.2%) and Cu (93.3%) using the conventional and the MW Tessier extraction methods, however, Pb extraction efficiency was excessively higher (442.5%) in MW extraction method as compare to Tessier sequential. In their successive study, almost similar findings were reported by Perez-Cid et al. [87] for Cr, Ni, Pb and Zn (recoveries between 93.9 and 102.3%). Kuo et al. [79] observed that at a solid to liquid (S/L) ratio of 0.17, 85% and 79% of Cu was leached from industrial sludge after 10 min of MW assisted treatment (800 W) using nitric and sulfuric acid, respectively; however, 81% and 79% of Cu was leached after 48 h of traditional acid extraction method using nitric and sulfuric acid, respectively. Therefore, the leaching time associated with the MW procedure was shorter and the leaching efficiency was greater than the traditional acid extraction method. The extraction process is environmentally and economically attractive because it can detoxify industrial sludge and remove valuable metals for reuse. Jamali et al. [88] studied the effects of the MW treatment on the extraction of Cd, Cr, Cu, Ni, Pb and Zn from the sewage sludge, and they observed overall metal recoveries of 95.3 to 104% with maximum heavy metals recovery at 900 W and 60 s reaction time. However, the higher recovery for Cu and Pb were achieved after 1.5 min reaction time at 900 W. Wu et al. [89] also reported that 90% of Cu can be extracted from coarse sludge ($<$9.5 mm) and fine sludge ($<$150 μm) after MW–H_2SO_4 (1 N) treatment at 800 W for 20 min reaction time.

Therefore, MW can be used as an efficient method for rapid and higher recovery of heavy metals as compared to time-consuming traditional acid extraction methods. MW heating is faster, thus supports faster dissolution than does conventional heating.

3.6.2.2. Heavy metals stabilisation. On the other hand, after industrial wastewater sludge passed through an extraction process to reclaim most of the metal ions in it, the concentration of metal ions in the residue is high and it still required to be treated by stabilisation techniques. Cement solidification fixes the heavy metal ions in the cement. However, cement solidification increases the volume of the sludge, and it reduces the useful lifetime of a landfill site. Conversely, MW process has been showed its potential to affect the stabilisation of heavy metal ions within the sludge [82].

The leaching concentration of Cu ions fells greatly from 179.4 to 6.5 mg/L at an Fe dose of 2% dry sludge weight (0.8 g-Fe/40 g-sludge) and 600 W power for 3 min reaction time [82].

Menendez et al. [90] concluded that MW technique is advantageous in substantial volume reduction with respect to the initial sludge and a solid residue that is more resistant to the leaching of organic substances and heavy metals than the char obtained by conventional pyrolysis. They reported that the significant reduction in the pore network of sludge solids would inhibit the lixiviation of heavy metals, since the surface area exposed to the lixiviating agent would also be reduced. MW treatment produces a solid residue, which is less porous than the solid produced from the electric furnace. The solids produced in the MW has a vitreous-like texture (very different from the porous texture of the solid produced in the electric furnace), and the heavy metals are occluded inside the vitreous matrix (Fig. 5).

Chan et al. [12] studied the effect of MW heating on the stabilisation of Cu ions in industrial sludge. They observed that on increasing the MW reaction time, the leaching concentration of Cu ions from the sludge with additives, increased suddenly because the stable compounds such as copper sulfide and copper phosphate were decomposed at the high temperature. A modified hybrid MW process with nitrogen gas was studied in order to limit the re-leaching at longer reaction time. They observed that, in the sodium sulfide system (1.73 g Na_2S), when the sludge (40 g) was treated by hybrid MW process of nitrogen (600 W–12 min), the Cu concentration in leachate decreased from 90 mg/L to 0.68 mg/L. They concluded that the hybrid MW process could not only control the sludge temperature to avoid the re-leaching, but also improve the effects of additives on sludge stabilisation. Hsieh et al. [91] applied 0.39 g Al powder dose at 800 W for 10 min reaction time and observed that the Cu leaching concentration decreased from 100 mg/L to < 5 mg/L. Copper leaching resistance increased with addition of Al metal powder and using higher MW power for longer processing time. Chen et al. [92] studied the effect of MW sintering to stabilise Cu-contaminated sludge. The Cu leaching from the sinters made from synthetic sludge with iron powder shows a significant decrease from 2082 mg/L to 15 mg/L within 5 min treatment at 800 W. Wu et al. [89] reported that the Cu stabilisation ratio reached up to 94% and the toxic characteristic leaching procedure (TCLP) yielded a concentration of copper < 5 mg/L (Cu declined from 54 to 3.4 mg/L) after 30 min of MW (800 W)/activated carbon/ Na_2HPO_4 treatment at a sludge/activated carbon/liquid ratio of 0.5/0.5/1. 89%.

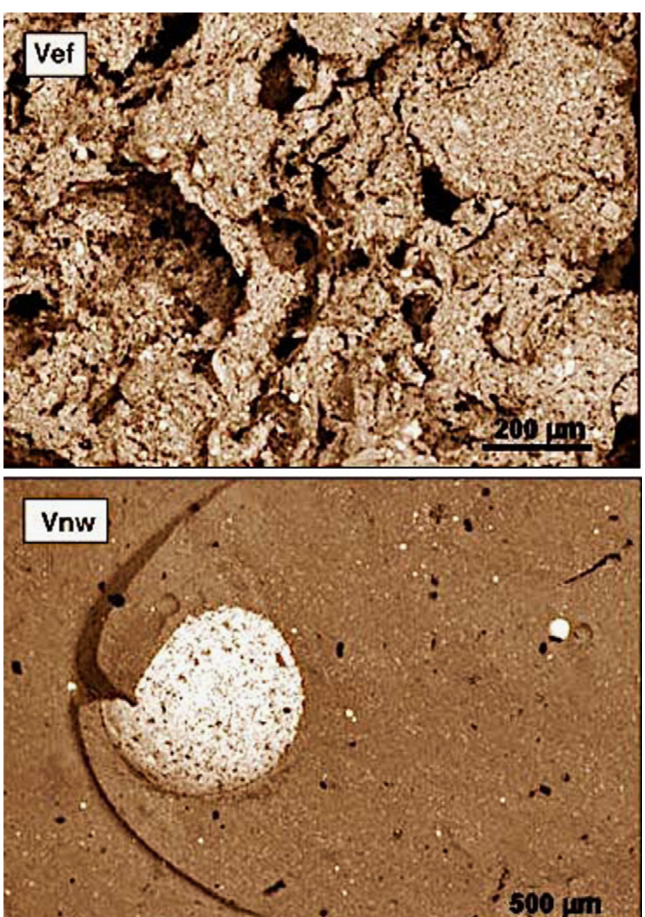

Fig. 5. SEM microphotographs of the solid residues obtained in the electric (Vef) and microwave furnaces (Vmw) [90].

Jothiramalingam et al. [93] observed that the Cu leaching reduced from 90.2 mg/L (control) to 2.52 mg/L at chitosan dosage of 4.0 g/40 g of solid sludge and MW heating at 800 W for 12 min. Other major heavy metal ions, such as Zn, Cr, Cd and Ni also exhibited a gradual decrease in leaching efficiency for the sludge treated at 800 W for 12 min with 4 to 6 g dosages of chitosan. In their subsequent work, Jothiramalingam et al. [7] studied the effects of sodium sulfide (Na_2S), barium manganate and alumina (α-alumina and γ-alumina) additives modified industrial sludge in the presence of MW heat treatment. They reported a significant reduction from 90 mg/L (control) to 5 mg/L in Cu leaching concentration on addition of 1.73 g/40 g dry solids dose of Na_2S with hybrid MW processing (600 W–9 min and 5 L/min N flow for 15 min). However, 1 g of barium manganate additive mixed industrial sludge microwaved at 600 W and 800 W, showed the complete stabilisation of Cd, Ni and Cu. Thus, barium manganate additive is act as a more selective stabilizing agent towards Cd, Ni and Cu ions due to ionic size and charge of the suitable heavy metal ion. Furthermore, the application of α-alumina and γ-alumina as an additive leads to a significant decrease in Cu leaching concentration from 132 mg/L (raw sludge) to 25 and 0.7 mg/L after treatment of industrial sludge with an α-alumina dose of 0.5 g/40 g sludge at 600 W for 9 min and furnace heating at 800 °C for 6 h and a γ-alumina dose of 0.5 g/40 g sludge at 600 W for 9 min and furnace heating at 800 °C for 6 h, respectively. Thus γ-alumina shows more promising results to stabilise Cu as compare to the use of α-alumina as an additive. Furthermore, MW heating achieved the same degree of heavy metals stabilisation in very short reaction time as compared to conventional heating.

Therefore, in summary it can be concluded that MW method is efficient to stabilise the different heavy metals (Cu, Zn, Cr, Cd, Ni) up to a higher degree (99%) or completely within a short reaction time (5–12 min) at 600–800 MW power input, while using different additives (Al, Fe, chitosan, barium manganate) and different systems (nitrogen and sodium sulfide) (Table 9). The solids generates during MW processing are more resistant to leaching than those obtained with conventional methods. Thus, MW method offers the environmentally safe disposal of industrial sludge to the landfill sites.

3.6.3. Bio-fuel recovery

As an alternative option for the recovery of maximum energy from sewage sludge (based on environmental safety and efficient sludge reduction considerations), pyrolysis has generated significant interest in recent years. The products of pyrolysis are bio-gas (non-condensable) and bio-oil (condensable and volatile), which have potential end uses and can be maximised by changing the

Table 9
Effect of MW treatment in heavy metals stabilisation.

Treatment conditions	Findings	References
0.8 g-Fe/40 g-sludge and 600 W-3 min	Leaching concentration of Cu ions fells greatly from 179.4 to 6.5 mg/L	[82]
Sodium sulfide system (1.73 g Na_2S), hybrid MW process of N (600 W-12 min)	Cu concentration in leachate decreased from 90 mg/L to 0.68 mg/L	[12]
0.39 g Al powder dose, 800 W-10 min	Cu leaching concentration decreased from 100 mg/L to <5 mg/L	[91]
800 W–5 min, iron powder for sintering	Cu leaching shows a significant decrease from 2082 mg/L to 15 mg/L	[92]
800 W–30 min of MW/activated carbon/Na_2HPO_4 treatment at a sludge/activated carbon/liquid ratio of 0.5/0.5/1. 89%	Cu stabilisation ratio reached upto 94% and the toxic characteristic leaching procedure (TCLP) yielded a concentration of copper <5 mg/L (Cu declined from 54 to 3.4 mg/L)	[89]
Chitosan dosage of 4.0 g/40 g of solid sludge , 800 W-12 min	Cu leaching reduced from 90.2 mg/L (control) to 2.52 mg/L. Complete stabilisation of Cr and Cd	[93]
1.73 g/40 g dry solids dose of Na_2S with hybrid MW processing (600 W-9 min and 5 L/min N flow for 15 min)	Significant reduction from 90 mg/L (control) to 5 mg/L in Cu leaching concentration	[7]
1 g of barium manganate additive mixed industrial sludge microwaved at 600 W and 800 W	Complete stabilisation of Cd, Ni and Cu	[7]
α-alumina dose of 0.5 g/40 g sludge at 600 W for 9 min	Cu leaching concentration decrease from 132 mg/L (raw sludge) to 25 mg/L	[7]
γ-alumina dose of 0.5 g/40 g sludge at 600 W for 9 min.	Cu leaching concentration decrease from 132 mg/L (raw sludge) to 0.7 mg/L	[7]

processing conditions [11]. However, it is important to mention that the conventional pyrolysis processes are always carried out in electric or gas furnaces that produce bio-oil with high polycyclic aromatic hydrocarbons (PAH), which are well-known carcinogenic substances [94]. Therefore, in view of the limitations of electric/gas furnace pyrolysis, MW-induced pyrolysis is considered to be a potential alternative for qualitatively and quantitatively optimizing the yield of pyrolysis oil [11]. Similarly, MW heating is considered advantageous over conventional heating methods for bio-gas recovery. The main advantages of microwave heating over conventional process are a higher heating efficiency and heating rate and therefore a greater saving of time and energy [95,96]. Furthermore, this form of heating might favor "in situ" heterogeneous catalytic reactions between the volatiles that evolved during the pyrolysis, the carbonaceous residue that is formed and the mineral content of the raw material [97].

3.6.3.1. Hydrogen and syn-gas (H_2+CO). Hydrogen is a promising alternative energy to fossil fuels. It is environmental friendly in that the by-product from its combustion with oxygen is water. Hydrogen has high energy (122 kJ/g) that is 2.75 times greater than that of hydrocarbon fuel. Hydrogen can be produced from chemical and biological processes [98]. Biologically, hydrogen can be produced by photosynthetic and fermentative methods that are more environmental friendly and less energy intensive than chemical processes. Recently, utilisation of activated sludge as the biological material for the production of renewable energy (i.e., hydrogen and methane using anaerobic digestion processes) has received much attention [99]. However, the poor efficiency of the hydrolysis that occurs in anaerobic processes demands the pretreatment of sludge to break down the bacterial cells, reduce the SRT and increase the hydrogen yield [10]. Therefore, the MW-pretreatment method has been tested and applied to solubilise the organic matter in the sludge and thus improve the rate of anaerobic digestion and facilitate the bioprocess of hydrogen production.

Furthermore, under the appropriate operating conditions (a MW heating temperature of 1000 °C), the pyrolysis and gasification of the sewage sludge take place and produce a gas with high CO and H_2 contents [90]. Syngas could be used as a clean alternative to fossil fuels in power generation or for the production of derived liquid fuels such as methanol, dimethyl ether and synthetic diesel [100]. To maximise the gas yield and to assess its quality as a source of hydrogen or syn-gas (H_2+CO), Lv et al. [79] investigated the pyrolysis of sewage sludge using MW (1000 W and 10 min, 1040 °C) and electrical ovens (24 min and 1040 °C) as the sources of heat and graphite and char as MW absorbers. Both gases were found to be produced in a higher proportion by MW pyrolysis than by conventional pyrolysis, with maximum values of 38% for H_2 and 66% for syn-gas. Moreover, this gas showed lower CO_2 and CH_4 concentrations of 50% and 70%, respectively, as compared to the gas obtained using the conventional process. Guo et al. [101] investigated hydrogen production during anaerobic digestion (inoculated a new strain of *Pseudomonas sp.* GZ1:EF551040) of MW-pretreated WAS (560 W, 2 min). They observed a remarkable increase in the specific hydrogen yield to 11.04 mL/g TCOD (18.28 mL H_2/gDS) at a lag time of 10 h. Thungklin et al. [10] observed the hydrogen production from waste sludge of a poultry slaughterhouse wastewater treatment plant (5% TS) by anaerobic batch fermentation. Sludge was heated with MW irradiation at 850 W for 3 min. They registered a higher hydrogen yield (12.77 mL H_2/g TCOD) than observed for the raw sludge (0.18 mL H_2/g TCOD).

The main outcomes of the efforts carried out to use MW heating in bio-gas production are summarised in Table 10. The gases produced from MW treatments have higher concentrations of syn-gas and lower concentrations of CO_2 and CH_4 than the gases obtained from conventional heating. The absence of moisture during the MW treatment was observed to favorably affect the gas composition. However, the presence of moisture in the conventional heating methods was observed to increase the concentrations of H_2 and CO_2 and reduce that of CO, which reduces the calorific value of gas. Furthermore, the production of syn-gas could also be enhanced during the MW pyrolysis of sludge with the addition of a suitable MW absorber. Therefore, MW offers an environmental friendly and a robust method for markedly enhancing gas production and producing less char as compared to conventional methods.

3.6.3.2. Bio-oil. Bio-oils (components of which according Dominguez et al. [102] are *n*-alkanes and 1-alkenes, aromatic compounds that range from benzene derivatives to PAH, nitrogenated compounds, long-chain aliphatic carboxylic acids, ketones, esters, monoterpenes and steroids), which are refined to high-quality hydrocarbon fuels, might have some advantages including facility of transport, storage and combustion and flexibility in marketing. Additionally, the bio-oil is a potential source of light aromatics such as benzene, toluene and xylene, which command a higher market value than raw oils. Conventionally, liquefaction of sludge is always carried out in an electric or gas furnace [11]. Unfortunately, many of the oils that are obtained at high pyrolysis temperatures (above 700 °C) contain high concentrations of PAHs, which are known to have carcinogenic or mutagenic characteristics [103]. For this reason, the use of these oils

Table 10
Effect of MW treatment on bio-gas recovery.

Treatment conditions	Findings	Reference
1000 W and 10 min, 1040 °C, graphite and char as MW absorbers	Higher yield of hydrogen (38%) or syngas (66%) over conventional treatment	[100]
560 W-2 min, use of a new strain of *Pseudomonas sp.* (GZ1:EF551040) during anaerobic digestion	A remarkable increase in specific hydrogen yield to 11.04 mL/g TCOD (18.28 mL H_2/g DS) at a lag time of 10 h	[101]
850 W-3 min	Higher hydrogen yield (12.77 mL H_2/g TCOD) than the raw sludge (0.18 mL H_2/gTCOD)	[10]

as fuel is limited because the combustion of PAH rich oil will lead to environmental pollution. Therefore, due to these limitations of electric/gas furnace pyrolysis, MW-induced pyrolysis, which allows the use of high temperatures with the minimum production of PAH, is considered a possible alternative for bio-oil recovery from waste sludge.

Dominguez et al. [102] reported that the pyrolysis of sewage sludge can be achieved by MW-assisted treatment using graphite as a MW absorber at 1000 °C. The pyrolysis oils produced have a high calorific value and a low proportion of compounds of environmental concern (such as PAH). Depending on the type of sludge, the oil produced by MW heating has a high proportion of long-chain aliphatic hydrocarbons, which is of significance for its use as fuel. Some important chemicals (from an industrial viewpoint) have also been obtained in high proportions, including benzene, toluene and styrene. The other compounds present in the oil contain long aliphatic chains that can be converted to aliphatic hydrocarbons with a high heating value. Use of graphite and char as MW absorbers allow temperatures as high as 1000 °C to be reached within a few minutes. The oil produced from MW pyrolysis is more aliphatic and oxygenated than are oils that are produced by conventional heating at the same temperature (1000 °C). In the case of MW-assisted pyrolysis, PAH with a high molecular weight are not formed; thus, the oil produced has a low toxic risk. However, secondary reactions are more important in conventional heating and lead to the formation of PAHs with up to six rings, including compounds of great environmental concern. Conversely, in MW heating, the degree of aromatisation is not high enough to produce such hazardous compounds [35,102]. Tian et al. [11] observed that for short residence times and high heating rates, MW pyrolysis under 400 W resulted in a maximum oil yield of 49.8 wt% in 6 min with negligible PAHs and with favorable characteristics such as a high calorific value (35.0 MJ/kg), low density (929 kg/m^3) and preferable chemical composition (29.5 wt% mono-aromatics). Furthermore, sulfur and nitrogen were mainly restrained to solids. Thus, MW irradiation is a good method for drying, pyrolyzing and gasifying sewage sludge in single step.

4. Relative merits and demerits of MW technique

4.1. Merits

- *Energy-efficient alternative to current heating technologies (Rapid and selective heating of materials through differential absorption):* Microwaves can be focused to heat materials directly internally so heat loss through convection and conduction can be minimised, whereas during conventional heating, materials are heated from outside to inside, so heat loss of these paths cannot be avoided [96], while transmitting energy (conventional heating).
- Highly specific and non-contact heating eliminate the requirement of direct contact between the heating source and the heated material [14,41,96]. This is a clear advantage that microwave heating has over conventional methods (bulk heating in furnaces).
- MW heating can reach the desired temperature quicker than conventional heating; and the process consumes less energy. The penetrating radiation and controllable electric field distributions, instantaneous power/temperature response and, enhancement in heating efficacy and control over the reaction are another major advantages of the application of MW irradiation [6,27,38,39,96].
- Microwave pretreatment has also the added benefits of athermal effects [104]. The existence of the MW athermal effect on WAS solubilisation and concomitant improvements in VS destruction and bio-gas production has been been reported by several researcher [25,34,41].
- *Improvement in product quality:* Unlike conventional methods, MW heating avoids degradation of product strength and surface properties caused by exposure to high temperatures, which leads to the improvement in product quality and yields specifically in case of sludge solubilisation, heavy metals stabilisation and, recovery of nutrients, bio-oil and bio-gas.
- *Rapid heat penetration*: MW energy penetrates into a homogeneous material, heating more uniformly than conduction methods. Heat need not "soak" through the material thickness, so interiors heat rapidly [105].
- *Selective heating:* Since different materials absorb MW energy at different rates, a product with many components can be heated selectively [105].
- *Increased flexibility:* MW heating units feature instant on/off. So no equipment warm-up or cool down is necessary [105].
- *Space savings:* MW heating equipment occupies 20 to 35% of the floor space of conventional heating units [105].
- Cool working conditions for the operating staff. Use of MW will improve the safety, including reductions in personnel exposure of potentially hazardous chemicals or materials for processing and disposition [96].
- Environment friendly natures of the process from the standpoint of renewable energy use and reduce combustion pollutants (SO*x*, NO*x*, CO*x*, particulates, PAHs,) [14,96].
- Treatment of pathogen laden sludge with MW irradiation offers to be a feasible option to produce the Class A sludge due to the lower-temperature requirement and shorter pretreatment time [19,20,38].
- *Usual Payback*: Payback based on energy savings is variable. Additional cost savings come from enhanced production rate, waste cutback, and quality of product.

4.2. Demerits

- Lack of fundamental data on material dielectric properties. Generally, the dielectric properties of a material are related to temperature, moisture content, density and material geometry [96].
- System design and development are found to be inhibiting the wider application of microwave technology to industrial processes. The majority of work undertaken in this field has been restricted to the laboratory [13,96]
- Industrial microwave heating application growth has been stunted by an apparent lack in the understanding of microwave systems [13].

5. Factors affecting the MW processing of sludge

Based on the results of the literature review, the MW processing of sludge in terms of COD solubilisation, sludge dewaterability, nutrient recovery, energy consumption and sludge solubilisation can be affected by the various factors that are summarised in Table 11.

Several other studies also investigated the effect of MW power input, irradiation time and treatment temperature on sludge solubilisation and subsequent anaerobic and aerobic digestion. The contradictory results are reported regarding the effect of *power input* on sludge solubilisation and subsequent bio-digestion. Some studies reported the enhancement in sludge solubilisation and bio-digestion efficiency with increasing the power input [57,106]. However, others reported the adverse effect of high power MW pretreatment on sludge solubilisation and biogas yield [25,36,107]. The so called *athermal effect* of MW technique was also studied by comparing the microwave heating and conventional heating processes. However, the conflicting results are reported regarding the biogas generation, when microwave in place of conventional heating was used. Some studies reported lower biogas generation [6], some other higher [32], and in some study, no evidence of the athermal effect of MW was found, as similar biogas production results were obtained with MW and conventional heating [25,107]. The *treatment temperature* has a key impact on the degree of sludge solubilisation. A remarkable improvement in sludge solubilisation has been reported with increasing the treatment temperature [8,42]. Therefore, proper optimisation of the above-discussed factors is necessary for the successful operation and wide application of MW-irradiation techniques for sludge treatment.

6. Discussion (core outputs of MW irradiation for sludge treatment)

A critical analysis of any treatment method or technique should be additionally evaluated based on the capital inputs and operational and maintenance costs involved, payback achieved from the technique, reduction of carbon footprints and environmental compatibility. This section presents the core outputs of the present review based on the reported results, conclusions and suggestions of the various research studies that were carried out globally on various aspects of sludge treatment using MW irradiation.

6.1. Benefits over conventional heating

MW heating is more effective than conventional heating. MW irradiation reduces reaction times as compared to conventional thermal treatment processes that required longer times to heat the sample. MW irradiation can be focused to heat materials directly internally to minimise heat loss through convection and conduction. Conversely, during conventional heating, materials are heated from the outside to the inside, so heat loss associated with these paths cannot be avoided [41].

6.2. Enhancement in sludge solubilisation and subsequent anaerobic digestion

MW irradiation is effective for improving sludge biodegradability by damaging activated sludge flocs structures and cell membranes and by releasing extracellular and possibly intracellular compounds (proteins, sugars and nucleic acids) with the solubilisation of particulates. This results in enhanced biogas production and VS removal. Thus, MW irradiation results in a greater recovery of biogas and is an important technique to reduce the SRT of the system.

6.3. Improvement in sludge dewaterability

MW irradiation is useful for improving the dewaterability of sludge. MW pretreatment of WAS can release the water that was originally bound to the particles and enhance dewaterability by altering the structure of EPSs, with the leakage of biopolymers, proteins, and polysaccharides to be used in anaerobic digesters. However, a short contact time slightly enhances sludge dewaterability, while a long contact time significantly worsens sludge dewaterability.

Table 11
Factors responsible to affect MW processing of sludge.

process	Factors	Description
Sludge solubilisation (in terms of COD and volatile solids)	*TS content MW energy and treatment temperature*	Higher SCOD yield will obtain for the samples with higher TS content, MW power and temperature. High MW irradiation energy with high temperature could not only break the flocs and release extracellular materials but also destroy cells and release intercellular materials from cells into the aqueous phase [29,30,36]
Sludge dewaterability	*Contact time*	The dewaterability of sludge depend on the time of exposure to the MW irradiation. A short contact time (30–90 s) slightly enhanced sludge dewaterability, while a long contact time significantly worsened sludge dewaterability. Increasing the contact time not only consumes more energy but also worsens the conditioning effects [24,45]
Nutrient recovery	MW irradiation power, operating temperature, heating period, TS concentration, and mixing	High operating temperature, longer reaction time and high TS concentration favorably affects the degree of phosphorus and ammonia solubilisation from sewage sludge [12,71]. Effect of mixing was observed more pronounced on higher nutrient solubilisation as compared to non-mixing conditions [60]
Energy consumption	Water content	Sludge water content influenced the efficiency of energy consumption thus low water content is necessary for improving the efficiency of energy use. However, more energy will be consume in increasing the temperature of WAS with higher water content because water has a high thermal capacity and can absorb more energy with a relatively small increase in temperature [33]
Sludge temperature	MW energy and contact time	Larger MW energy and shorter contact time is needed for the sludge temperature to reach the boiling point [57]

6.4. Significant inactivation of pathogens

MW irradiation achieved significant coliforms inactivation at lower temperatures and shorter reaction times as compared to conventional heating methods. It can produce environmentally safe sludge that can fulfill the class-A biosolids requirements. Therefore, MW irradiation of waste sludge is a promising and economical method for pathogen removal.

6.5. Environmentally friendly bio-fuel production

MW pyrolysis of sludge (at short reaction times and high heating rates) produces oils (bio-fuels) with high aliphatic and oxygenated characteristics and that do not contain environmentally harmful (carcinogenic and mutagenic) compounds such as heavy PAHs; thus, these oils have a low toxicity risk. A syngas of high calorific value (H_2+CO) can be produced at high yields from the MW pyrolysis of sewage sludge. This is an environmentally clean energy source that can be converted to liquid fuels, which can assist in minimizing environmental pollution.

6.6. Effective heavy metals recovery and stabilisation

MW irradiation is a rapid and efficient method, as compared to conventional procedures, to recover the heavy metals from sludge. Solids produced in the MW treatment are more resistant to leaching, i.e., are less porous and more resistant to the lixiviation of organic substances and heavy metals, than those obtained in conventional heating/pyrolysis. The MW heating process with a few additives provides efficient heavy metal stabilisation for industrial waste sludge. The MW process saves time as compared to traditional heating processes for sludge stabilisation.

6.7. Effective nutrient recovery

Individually, or in combination with other chemical methods, MW-irradiation technology could facilitate the significant release of nutrients (such as phosphate and nitrogen) from sludge in a very short period of time and without any addition of chemicals. This is an important step for nutrient recovery through struvite crystallisation. MW-irradiation technology proves to be superior in nutrient recovery from sludge over other traditional treatment methods. The recovery of a useful product (struvite) from waste sludge is important for maintaining a sustainable supply of phosphorus by decreasing the demand for phosphate rock and increasing the amount of recycled phosphorus.

6.8. Effective Hybrid treatment

The use of MW irradiation in combination with other chemical methods (hybrid treatment) has been shown to synergistically enhance the efficiency of the whole process in terms of improvement in COD and the solubilisation of solids, which consequently enhance the digestion performance in terms of higher organics removal and biogas production. MW irradiation can be used to facilitate the recovery of valuable products from sludge, such as orthophosphate, ammonia, metals and bio-fuels. Thus, due to the synergistic effects, hybrid pretreatments can provide a more effective and economical solution compared to individual MW pretreatment methods for sludge treatment.

6.9. Economical facets and potential paybacks

Economic feasibility is a function of local variations in energy costs, environmental laws and labor costs balanced with the properties of finished materials or parts, improvements in yield or productivity, and the markets for the products [18].

Few studies have compared the energy efficiency of MW-irradiation and ultrasonic techniques for sludge pretreatment and they concluded that the MW irradiation energy required per unit mass of sludge is lower than the energy required for sonication to attain the same degree of solubilisation, which is likely to be the best option for enhancement of methane generation [26,27]. This shows that MW irradiation may be a rapid and cost-effective technique for sludge pretreatment. Introducing the MW pretreatment to a digestion system can increase the rate of stabilisation and reduce the SRT from 20 days to 10 or even 5 days [41]. By decreasing the SRT, sludge could be stabilised in smaller reactors, which would save energy and lower heating costs, construction costs and space requirements. Better sludge dewaterability using MW irradiation, resulting in the generation of smaller volumes of sludge for disposal, will also reduce the cost of transportation and disposal and space requirements. Factors such as plant capacity, sludge characteristics, energy requirements, disposal costs and regulatory requirements are major factors that would affect economic analyses. Nevertheless, to make MW pretreatment incorporation into the system feasible, it is imperative to use the excess heat that is produced after MW heating [41].

Consumption parts that have to be thought for pretreatment are the cost for buying and for running the MW pretreatment. On the other hand, saved parts as addition of pretreatment process are the cost for reducing digester volume because of an enhanced rate of treatment efficiency and more energy rich biogas production [27]. The implementation of a heat-recovery system could reduce the capital and electrical expenses associated with MW heating by over 50% [73].

6.9.1. Lucrative by-products

Although the initial capital cost of MW equipment is high, this can be offset by the economic benefits attained by the yield of saleable by-products. The pyrolysis of hydrocarbon-based wastes produces pyro-gas, oils and chars that can be further treated and sold. There is evidence that markets are available for these products. Alternatively, the by-products can be reused in the MW process itself and provide further energy and cost savings. For example, the gas and oils can be employed as secondary fuels, thereby reducing fossil–fuel consumption, and the char can be mixed into the feed material and employed as a MW absorber. The absence of air in pyrolytic processes prevents the formation of SO_X and NO_X in the flue gases, thus reducing the need for larger air-pollution control devices. Indeed, MW technologies are actually applicable to the control of such emissions [13].

Therefore, based on the above discussed benefits of the MW technique, it can be said (concerning environmental and economic issues) that the application of the MW technique in the field of sludge treatment is in good agreement with the principles of green chemistry [110]. Table 12 shows how the R&D philosophy of any process or technique should be in harmony with the principles of green chemistry.

Furthermore, the economic benefits of microwave processing are difficult to define in a general way. The decision to use microwave processing for any application must be based on an analysis of the specific processes involved. Important factors include the location of the processing facility, the product requirements, possible property improvements, alternative sources of energy, availability of capital and the balance between energy costs, labor costs, capital costs, and the value added to the product. In most successful applications of MW-irradiation techniques, factors other than energy account for the savings realised from MW processing; improvements in productivity and material properties as well as savings in time, space, and capital equipment are probably the best basis for selecting MW techniques

Table 12
R&D philosophy in harmony with the principles of green chemistry [108].

	Environmentally	Economically
Atom economy	***Minimal by-product formation.***	***More from less—incorporate total value of materials***
Solvent reduction	Less solvent waste.	Higher throughput, less energy
Reagent optimisation	Catalytic, low stoichiometry, recyclable reagents minimise usage	Higher efficiency—higher selectivity
Convergency	***Due to increased process efficiency***	***Higher efficiency***—fewer operations
Energy reduction	***From power generation,*** transport, and use	***Reduced energy reflects increased efficiency, shorter process, mild conditions***
In-situ analysis	Reduced possibility for exposure or release to the environment	Real-time data increases throughput and process efficiency, fewer reworks
Safety	***Non-hazardous materials reduce risk of exposure, release, explosions and fires***	***Worker safety and reduced down time, Reduced time on special control measures***

over conventional processes. Furthermore, hybrid systems may also offer additional savings over either an MW or conventional system alone [18].

However, the value proposition and quantification of benefits are difficult at this stage, as no industrial-scale data are available and all of the studies addressing the different applications of MW irradiation in sludge treatment were carried out only at the lab scale. Therefore, the scaling-up of MW techniques is a prerequisite to substantiate the economic aspects of full-scale application.

7. Future research directions

For the broader application of MW irradiation process for sludge treatment, progressive efforts are needed to a greater extent. Based on the extensive literature review and the recommendations and suggestions of several researchers and technical reports [13,18,32,105], the following recommendation for potential research avenues can be put forward:

- System design and development inhibit the wider application of MW technology to industrial processes. The majority of work undertaken in this field has been restricted to the laboratory. A scaling-up of the processes involved is required to estimate the return on the investment and operating costs of pilot- or full-scale MW systems, in comparison with the higher energy output represented by the higher biogas production. Therefore, to comprehend the potential benefits of MW and hybrid processes, efforts are needed to scale-up processes and system designs to large-batch or continuous processes. This can include model simulation, system design and integration, and development of an understanding of the costs and benefits involved in moving to production scale. The modeling also requires characterisation of the thermal and physical properties of materials, including thermal conductivity and diffusivity, thermal expansion, and temperature-dependent dielectric properties.
- Operating parameters, such as material characteristics and throughput, irradiation time, frequency and power, penetration depth, and cavity design, has been found to determine the extent to which a successful treatment is achieved.

7.1. Material characteristics

Every material's ability to be heated under exposure to MW energy is determined by a property called the loss factor. Materials with loss factors of between 0.01 and 1 generally heat adequately at MW frequencies. However, these values should be viewed as guidelines only, as the loss factor is dependent on temperature, frequency, and moisture content. A material's sensitivity to rapid heating must also be considered. The rate at which the material can be heated without damage limits the speed at which MW energy can be applied.

7.2. Penetration depth

MW energy may penetrate to 50 cm for materials with a low-loss factor but only to a few centimeters for high-loss materials such as water.

7.3. Frequencies

Most applications use 2450 MHz because the MW units are smaller and easier to work with and the generator development is more advanced. However, 915 MHz is more economical for applications requiring more than 60 kW of power. Deeper penetration into the material can also be achieved with 915 MHz.

7.4. Power

A material's heating rate is governed by the amount of MW power that is applied to it. Power level requirements are calculated based on the properties of the material being heated for a particular throughput and on the initial and final temperatures. The power level and the estimate of its efficiency are then confirmed with equipment tests. Material temperatures are adjusted by precise control of the power level.

Control of these parameters is important for the advantages of MW to be realised. Without control, non-uniform heating can occur, resulting in the formation of hot spots. These areas of high temperature can result in an unexpected heating performance and therefore can reduce the overall treatment efficiency and lower the effective energy utilisation.

- **Microwave safety and health related issues** [18,109]: As microwave power levels for industrial processing systems increase, potential hazards associated with exposure to radiation become more important. At present, the only confirmed effect is warming, from the conversion of electromagnetic energy to heat. Thus, microwave exposure standards are based on the thermal effects of exposure. The current safety standard for microwave ovens is an emission specification that limits emissions up to 5 mW/cm^2 at a distance of 5 cm from microwave oven. To minimise exposure, the microwave system needs to be designed with effective leakage suppression, viewing or ventilation screens, and an interlock system on doors and access apertures to shut off power when doors are opened.

8. Conclusions

This literature review revealed that the application of MW-irradiation techniques offers great advantages over conventional

methods of sludge treatment and in the production of environmentally clean and value-added products.

- MW irradiation effectively disintegrates the sludge and thus increasing the readily biodegradable portion in liquid phase of sludge. Which ultimately leads to enhanced VS reduction, improvement in sludge dewaterability and biogas production during the anaerobic digestion and reduces the SRT remarkably.
- Combination of MW with alkaline, acidic and advances peroxidation methods is advantageous to reduce the MW energy consumption and corresponding treatment cost for achieving the similar solubilisation yield, as by MW alone. Moreover, higher biogas generation can be observed for hybrid pretreatment methods.
- MW irradiation is capable to produce environmentally safe (pathogen-free) sludge, which reduces exposure to pathogens and allows the sludge to be used for land applications.
- MW could be a promising method for enhanced nutrient (phosphate and nitrogen) recovery from waste sludge for sustainable supply of nitrogen and phosphorus and reduce the burden on phosphate rocks by recycling nutrients.
- MW could be used as an efficient method for rapid and higher recovery of heavy metals as compared to time-consuming traditional acid extraction methods.
- Solids generates during MW processing are more resistant to heavy metals leaching than those obtained with conventional methods. Thus, MW method offers the environmentally safe disposal of industrial sludge.
- Pyrolysis and gasification of the sewage sludge using MW irradiation would markedly enhanced energy-rich syngas production having a high calorific value (lower concentrations of CO_2 and CH_4 and lower production of char as compared with conventional methods) and bio-oil with a low PAH content.

Nevertheless, following future research and development are needed:

- Optimisation of the operating conditions to enhance sludge solubilisation, biogas generation and biosolids minimisation.
- Scale-up the lab-scale units to full-scale system.
- Investigation of fate of spore and cyst forming organisms and Enteroviruses under low and high MW thermal treatment conditions during sludge pretreatment and subsequent biodigestion.
- Evaluate possible synergisms between MW coupled hybrid sludge treatment methods.
- Identify the dielectric properties of materials.
- Reuse of waste heat in order to achieve an efficient sludge treatment scheme.
- Minimise costs and lower carbon footprints.

These approaches would be interesting and attractive for future research and for optimizing the process and developing industrial-scale MW sludge treatment systems.

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